On Jupiter's Rate of Rotation

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ABSTRACT

It is suggested that the apparent lag of Jupiter's mean rotation rate in extratropical latitudes (System II) behind the rotation rate of Jupiter's radio emissions (System III) is caused by the difference between phase speeds and true speeds in extratropical latitudes. An estimate of the difference based on the formula for the phase speed of Rossby waves agrees with the difference calculated from the two rotation rates.

Observations of Jupiter over many decades have not yielded a unique result for its rotation period. Rather, three different rotation periods have come to be accepted for calculating longitudinal positions (Newburn and Gulkis, 1973). Longitudes in System I are based on a rotation period of 9 hr 50 min 30.0 sec, corresponding to the mean rotation period of visual features less than 10° of latitude from the equator; longitudes in System II are based on a rotation period of 9 hr 55 min 40.6 sec, corresponding to the mean rotation period of visual features at latitudes greater than 10°; and longitudes in System III are based on a rotation period of 9 hr, 55 min, 29.8 sec, corresponding to the mean rotation period of radio emissions from the magnetosphere. Since the radio emissions are likely to be closely linked to the planet's interior, the most plausible interpretation of these rotation periods is that System III represents the "true" rotation period, while Systems I and II reflect motions in the atmosphere relative to the "true" rotation rate (Newburn and Gulkis).

If we adopt this interpretation, then it is a straightforward matter to calculate the apparent mean zonal motions in high and low latitudes implied by the rotation rates of Systems I and II. If τ' is the apparent rotation period, then

$$\tau' = \frac{2\pi R \cos\theta}{\Omega R \cos\theta + u'}, \tag{1}$$

where R is the planetary radius, θ the latitude, Ω the true angular rate of rotation, and u' the apparent mean zonal speed (measured as positive for westerly flow). If we define τ to be the true rotation period, $2\pi/\Omega$, and t to be the deviation from the true rotation period, we can solve Eq. (1) to find u' in terms of t. Since $t \ll \tau$, we find to a good approximation

$$u' \approx \frac{-2\pi R \cos\theta}{\tau} \frac{t}{\tau}. \tag{2}$$

Taking $R = 7.16 \times 10^9$ cm and $\tau = 2\pi/\Omega = 3.62 \times 10^4$ sec (System III) for Jupiter, and using $\theta = 0°$ and $30°$ as typical for Systems I and II, respectively, we calculate

$$u'(\mathrm{I}) = 103 \text{ m sec}^{-1}, \tag{3}$$

$$u'(\mathrm{II}) = -3.2 \text{ m sec}^{-1}. \tag{4}$$

On Jupiter the true zonal wind u in mid and high latitudes is likely to obey the thermal wind equation, at least in the mean (Stone, 1967), i.e.,

$$2\Omega \sin\theta \frac{\partial u}{\partial z} = -\frac{g}{T_0 R} \frac{\partial T}{\partial \theta}, \tag{5}$$

where z is the vertical height, g the acceleration of gravity, T the temperature, and T_0 the global mean temperature of the levels in motion. If we identify the apparent mean motions, u' (II), with the true motions, since the apparent motions refer to levels high in the atmosphere, Eq. (5) requires a positive mean temperature gradient, i.e., temperatures in high latitudes higher on the average than those in low latitudes. This would be in conflict with the only known source for the mean meridional temperature gradient, namely, differential solar heating. It is the purpose of this note to point out that the mean apparent velocity of System II can be explained much more readily as a phase velocity than as a true velocity. This possibility has been neglected in studies of the extratropical currents (Ingersoll and Cuzzi, 1969; Chapman, 1969).

We can use Eq. (5) to obtain an estimate of the true zonal velocity in mid and high latitudes. In order of magnitude Eq. (5) can be written as

$$u \sim \frac{-gH}{2\Omega \sin\theta T_0 R} \frac{\partial T}{\partial \theta}, \tag{6}$$

where H is the scale height. The small temperature gradients on Jupiter lead to dynamical fluxes sufficiently small that the radiative meridional temperature gradient approximates the actual mean meridional gradient (Stone, 1972). On a rapidly rotating planet the insolation varies as $\cos\theta$, and the meridional temperature distribution in radiative equilibrium will be given by

$$T = T_0 \left[\frac{(4/\pi) \cos\theta + q}{1+q} \right]^{\frac{1}{4}}, \tag{7}$$

where q is the ratio of the strength of the internal heating to the strength of the solar heating. If we use this equation to calculate the gradient in Eq. (6), use the same values as before for R and Ω, and take $T_0 = 160$K, $g = 2600$ cm sec^{-2}, $H = 20$ km, $\theta = 30°$, $q = 1.7$ (Aumann *et al.*, 1969), we find

$$u(\mathrm{II}) \approx 2.4 \text{ m sec}^{-1}. \tag{8}$$

It is the discrepancy between (4) and (8) which we wish to explain.

The apparent rotation rate in System II has been determined by following atmospheric features (presumably cloud formations) which range in size from 1° to 25° in latitude and longitude, i.e., from 1000 to 25,000 km in size (Peek, 1958). All of these features are sufficiently large that the Rossby number associated with them is very small. For example, even a 1° feature at 30° latitude with the value of u given by Eq. (8) has a Rossby number of only 1.4×10^{-2}. Consequently, we can calculate the phase speed c from the formula for barotropic Rossby waves (Holton, 1972, p. 180), i.e.,

$$c = u - \frac{2\Omega \cos\theta L_x^2 L_y^2}{4\pi^2 R (L_x^2 + L_y^2)}, \tag{9}$$

where L_x and L_y are the wavelengths of the disturbance in the zonal and meridional directions, respectively. If we identify the scale of the observed features with a half-wavelength, by analogy with terrestrial cyclones and anticyclones, then the phase speed for a circular feature of diameter D would be given by

$$c = u - \frac{\Omega \cos\theta D^2}{\pi^2 R}. \tag{10}$$

For example, using the same values of R and Ω as before, we find that a feature at 30° with a 5000 km diameter would lag behind the mean flow by an amount

$$u - c = 5.3 \text{ m sec}^{-1}. \tag{11}$$

Comparing this lag with the difference between Eqs. (4) and (8), we see that both the magnitude and sign of the discrepancy between $u'(\mathrm{II})$ and $u(\mathrm{II})$ can be explained by identifying u' with c.

The above estimates are, of course, very rough. For example, the range of sizes of the observed features is large enough that speed differences anywhere in the range $0 < u - c < 100$ m sec^{-1} can occur on occasion. A definitive demonstration that the lag of System II behind System III is due to a phase speed effect would require a new analysis of the observations which allowed for the difference between the phase speed and true speed for each separate feature. Nevertheless, our estimates do establish the plausibility of the hypothesis. The occurrence of differences as large as 100 m sec^{-1} between true speeds and phase speeds raises the possibility that the apparent distribution of currents in extratropical latitudes may differ considerably from the true distribution.

REFERENCES

Aumann, H. H., C. M. Gillespie, Jr., and F. J. Low, 1969: The internal powers and effective temperatures of Jupiter and Saturn. *Astrophys. J.*, **157**, L69–L72.

Chapman, C. R., 1969: Jupiter's zonal winds: Variation with latitude. *J. Atmos. Sci.*, **26**, 986–990.

Holton, J. R., 1972: *An Introduction to Dynamic Meteorology.* New York, Academic Press, 319 pp.

Ingersoll, A. P., and J. N. Cuzzi, 1969: Dynamics of Jupiter's cloud bands. *J. Atmos. Sci.*, **26**, 981–985.

Newburn, R. L., and S. Gulkis, 1973: A survey of the outer planets Jupiter, Saturn, Uranus, Neptune, Pluto, and their satellites. *Space Sci. Rev.*, **14**, 179–271.

Peek, B. M. 1958: *The Planet Jupiter.* London, Faber and Faber, 283 pp.

Stone, P. H., 1967: An application of baroclinic stability theory to the dynamics of the Jovian atmosphere. *J. Atmos. Sci.*, **24**, 642–652.

——, 1972: A simplified radiative-dynamical model for the static stability of rotating atmospheres. *J. Atmos. Sci.*, **29**, 405–418.